On the effect of small-scale oceanic variability on topography-generated currents

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Abstract.

Small-scale oceanic motions, in combination with bottom topography, induce mean large-scale along-isobaths flows. The direction of these mean flows is usually found to be anticyclonic (cyclonic) over bumps (depressions). Here we employ a quasigeostrophic model to show that the current direction of these topographically induced large-scale flows can be reversed by the small-scale variability. This result addresses the existence of a new bulk effect from the small-scale activity that could have strong consequences on the circulation of the world's ocean.

Introduction

Small-scale ocean motions have an important effect on oceanic flows several orders of magnitude larger than them. The best-known bulk effect of small-scale processes is a substantial contribution to the transport of heat, salt, momentum, and passive tracers in all parts in the world's oceans. This effect is usually included in ocean circulation models by modifying the transport and mixing properties of the fluid from their molecular values to larger ones, giving rise to eddy-diffusion approaches of increasing sophistication and predictive power [*Neelin and Marotzke,* 1994]. The transport processes parametrized by these effective changes of the diffusive fluid properties have been shown to control important aspects of the Earth's climate [*Danabasoglu et al.,* 1994].

Beyond eddy diffusion approaches, physical effects of small-scale activity are still poorly understood. For this reason, the nature and variability of small-scale oceanic motions have been exhaustively examined in different oceanographic contexts [*Wunsch and Stammer,* 1995]. Given the nature of small-scale activity – disordered, fluctuating and turbulent – a contribution to diffusion and dispersion effects is obvious on physical grounds. But a more coherent influence of processes occurring at small-scales on large scales motions is unexpected unless some oceanographic factor is able to get a significant mean component out of the fluctuating behavior. Bottom topography is one of such factors breaking the symmetry of the fluctuation statistics, and thus provides a dynamical link for energy transfer from the small to the large scale.

Evidence has been accumulated in the last decade showing that mean flows

following the topographic contours are often found in the vicinity of topographic features of different scales [*Klein and Siedler,* 1989; *Pollard et al.,* 1991; *de Madron and Weatherly,* 1994; *Brink,* 1995]. These topographically generated currents have been shown to influence both local and global aspects of the Earth's climate [*Dewar,* 1998]. For example, large-scale motions related to topographic anomalies have been found in the North and South Atlantic playing a major role in determining regional circulation and climatic characteristics [*Lozier et al.,* 1995; *Saunders and King,* 1995].

Coriolis force, topography and fluctuations have been pointed out as the main ingredients to generate these along-isobaths coherent motions [*Alvarez et al.,* 1997; *Alvarez and Tintoré,* 1998; *Alvarez et al.,* 1998]. Briefly, Coriolis force links topography to the dynamics of ocean vorticity. Thus changes in ocean depth provide a symmetry breaking factor distinguishing according to their vorticity content otherwise isotropic mesoscale fluctuations. The result is that the mean effect of small-scale fluctuations does not average to zero yielding the existence of mean flows. Finally, the topographic structure determines the circulation patterns of the originated currents.

On the basis of present knowledge, anticyclonic (cyclonic) tendencies are expected over bumps (depressions) for generated mean flows over topography. However, *Alvarez et al.* [1998] pointed out that these circulations tendencies could be strongly dependent on the properties of the small-scale variability. They theoretically addressed the possibility that the above mentioned circulation pattern could be even reversed (cyclonic (anticyclonic) circulations over bumps (depressions)) by the action of the small scales. The same effect is predicted when considering bottom friction instead of viscosity as the

damping mechanism [*Alvarez et al.,* 1999]. The present Letter attempts to elucidate, by means of computer simulations, if the direction of these mean flows is sensitive to the statistical characteristics of the small-scale, as it was argued on theoretical grounds.

Model and results

To explore in detail the possible relations between large and small scales in the presence of topography an ideal ocean represented by a single layer of fluid subjected to quasigeostrophic dynamics will be considered. Baroclinic effects which in real oceans give rise to meso-small scale activity are modeled here by an explicit stochastic forcing with prescribed statistical properties [*Williams,* 1978]. This term might also be considered as representing any high frequency wind forcing components and other processes below the resolution considered in the numerical model. This random forcing, in combination with viscous dissipation, will bring the ocean model to a statistically steady state. While highly idealized, the simplifying modeling assumptions above arise from our interest in isolating just the essential processes by which small-scale variability leads to topography-generated currents.

Within our approximations, the full ocean dynamics can be described by [*Pedlosky,* 1987]:

$$\frac{\partial \nabla^2 \psi}{\partial t} + \left[\psi, \nabla^2 \psi + h\right] = \nu \nabla^4 \psi + F \ , \tag{1}$$

The ocean dynamics described by Eq. (1) is an f-plane quasigeostrophic model

where $\psi(\mathbf{x},t)$ is the streamfunction, $F(\mathbf{x},t)$ is the above mentioned stochastic vorticity input, ν is the viscosity parameter and $h = f\Delta H/H_0$, with f the Coriolis parameter, H_0 the mean depth, and $\Delta H(\mathbf{x})$ the local topographic height over the mean depth. The Poisson bracket or Jacobian is defined as

$$[A,B] = \frac{\partial A}{\partial x}\frac{\partial B}{\partial y} - \frac{\partial B}{\partial x}\frac{\partial A}{\partial y}\ . \tag{2}$$

A set of numerical simulations has been carried out to determine the dependence of the large scale pattern circulation on the structure and variability of the small-scales. The description of the numerical model and different parameters employed in the simulations are summarized in Appendix A. A randomly generated bottom topography is used in all the cases. As a way of changing in a continuous manner the statistical properties of the forcing $F(\mathbf{x},t)$ we assume it to be a Gaussian stochastic process of zero mean, white in time, and spatial spectrum given by $S(k) \propto k^{-y}$, where k is the wavenumber. A positive exponent y represents relative-vorticity fluctuations more dominant at the large scales, whereas negative y represents fluctuations dominant at the smaller scales. The distribution of fluctuation variance among the scales can thus be controlled by varying y. The spectrum of the energy input corresponding to the above stochastic vorticity forcing is also white in time, with a wavenumber dependence given by the relation $E(k) = S(k)\ k^{-2}$. We have started first considering a situation where the small-scale variability is described by $S(k) \propto k^0$. This power-law has been observed for vorticity forcing induced by winds in the Pacific ocean [*Freilich and Chelton,* 1985]. The model has been integrated until a stationary state is achieved. Figure 1b shows the

mean currents obtained from this specific simulation. In the mean state the currents do not average to zero, despite the isotropy of the fluctuations and dissipation. Instead the final mean state is characterized by the existence of large-scale mean currents strongly correlated with bottom topography. The spatial correlation coefficient between the streamfunction and the bottom topography is for this case 0.85. This positive spatial correlation implies the existence of mean anticyclonic (cyclonic) circulations over bumps (depressions). As a next step, we have modeled the action of small-scales as a noisy process with a correlation described by the power-law $k^{4.8}$. This spectrum describes a situation where the small-scale variability is more energetic than the one induced by the previous k^0 power-law. The response of the system is drastically changed by this small-scale activity. As shown in Figure 1c the mean state of the ocean displays a pattern of circulation practically uncorrelated with bottom topography. Specifically, the spatial correlation coefficient is 0.091. Increasing again the exponent of the power law to $S(k) \propto k^6$, we obtain the generation of mean currents anticorrelated with bottom topography, as it can be observed from Figure 1d. The spatial correlation coefficient is -0.77 in this case of high small-scale activity, indicating the existence of mean cyclonic (anticyclonic) motions over bumps (depressions). Note that Figures 1c and d display topography-generated currents much weaker than those obtained for the k^0 power-law case, Figure 1b. This feature comes from the scale-selective character of the viscosity, more efficient at small scales where the forcing energy is most localized in the $k^{4.8}$ and k^6 cases. Besides this effect, it should also be mentioned that forcing with a k^0 spectral power-law directly provides more energy input to the large-scale components than the

$k^{4.8}$ and k^6 forcings. Additional numerical simulations, for different initial conditions and noise and topography realizations, consistently confirm the results of the simulations presented in Fig. 1, that is the sensibility of the large-scale circulations not only to the particular structure of the underlying topography but also to the characteristics of the small-scale variability of the environment. In particular, as the small-scale content in the vorticity forcing is augmented with respect to the large-scale one, mean currents are always seen to reverse direction.

Conclusion

On the basis of the property of potential-vorticity conservation, anticyclonic (cyclonic) motions are traditionally expected over topographic bumps (depressions) [*Pedlosky,* 1987]. If potential vorticity is not preserved because of the presence of some kind of forcing mechanism, then different circulation patterns can be generated. Small-scale activity constitutes a systematic and persistent forcing of the circulation in the whole ocean. Due to the relatively small and fast space and time scales that characterize this variability, the physical characteristics of this forcing are usually described in terms of their statistical properties [*Williams,* 1978]. In other words, small-scale activity can be considered as a fluctuating background in which the large-scale motions are embedded. The relevance of the role played by this fluctuating environment in modifying the transport and viscous properties of the large scales is widely recognized. Beyond these diffusive and viscous effect of the small-scale activity, the numerical results presented in this Letter show that in the presence of bottom

topography, statistical details of the variability of the small-scales can induce different large-scale oceanic circulations. The strength of this effect will be affected by the spectral characteristics of the topographic and forcing fields as well as by the real baroclinic nature of the ocean. Preliminary computer simulations indicate that the strength of the mean currents increases when the topography contains more proportion of large-scale features. This effect and the dependence of the current direction on the forcing spectral exponent, presented in Fig. 1, nicely validates the theoretical results in [*Alvarez et al.,* 1998]. Extension of the theoretical methods to the baroclinic case is in progress. However, a complete analysis of the influence of different forcings and topography shapes can only be addressed numerically. The shape of the topography was already shown to play a fundamental role in the energy transfer between different scales in baroclinic quasigeostrophic turbulence [*Treguier and Hua,* 1988]. Finally, the results shown in this Letter stress the need for a better observational characterization of the space and time variability of oceans at small-scales in order to achieve a complete understanding of the large-scale ocean circulation.

Appendix A: Numerical model description

Numerical simulations of Eq. (1) have been conducted in a parameter regime of geophysical interest. A value of $f = 10^{-4}s^{-1}$ was chosen as appropriate for the Coriolis effect at mean latitudes on Earth and $\nu = 200m^2s^{-1}$ for the viscosity, a value usual for the eddy viscosity in ocean models. We use the numerical scheme developed in *Cummins* [1992] on a grid of 64×64 points. The distance between grid points corresponds to 20

km, so that the total system size is $L = 1280$ km. The algorithm, based on Arakawa finite differences and the leap-frog algorithm, keeps the value of energy and enstrophy constant when it is run in the inviscid and unforced case. The consistent way of introducing the stochastic term into the leap-frog scheme can be found in *Alvarez et al.* [1997]. The amplitude of the forcing has been chosen in order to obtain final velocities of several centimeters per second. The topographic field is randomly generated from a isotropic spectrum containing, with equal amplitude and random phases, all the Fourier modes corresponding to scales between 80 km and 300 km. The model was run for 5×10^5 time steps (corresponding to 206 years) after a statistically stationary state was reached. The streamfunction is then averaged during this last interval of time.

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Figure 1. a) Random bottom topography. Maximum and minimum topography heights are $500m$ and $-599m$, respectively, over an average depth of $5000m$. b) Computed mean streamfunction $\psi(\mathbf{x}, t)$ in $m^2 s^{-1}$ for the case when the small-scale variability is described by a spectral power law k^0. Bottom topography levels have been superimposed (black lines) as reference over the streamfunction field. The strong correlations between the streamfunction and topography are clear from this figure. c) Same as b) but with power spectra law $k^{4.8}$. In this case the flow remains practically uncorrelated with the underlying topography (black lines). d) For k^6 the flow is anticorrelated with the topography.